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CHARACTERIZATION OF THE PROTOTYPES PERFORMANCE

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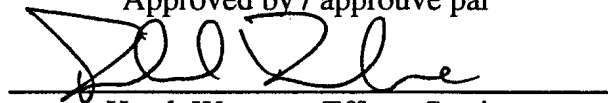DREV - TM -9719
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LIGHTWEIGHT ENHANCED TRENCH OVERHEAD PROTECTION SYSTEM (LETOPS): CHARACTERIZATION OF THE PROTOTYPES PERFORMANCE

by

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Date

ABSTRACT

This memorandum describes a test program completed at Defence Research Establishment Valcartier (DREV) to study the performance of two Lightweight Enhanced Trench Overhead Protection Systems (LETOPS) prototypes manufactured under contract by two Canadian firms. Both prototypes were submitted to the detonation of ten 155-mm HE artillery shell seven meters above the trenches. The detonations were performed consecutively, and the systems were adjusted after each detonation, whenever required. The test results are presented, summarily analysed and discussed.

RÉSUMÉ

Ce mémorandum décrit un programme expérimental récemment complété au Centre de recherches pour la défense Valcartier (CRDV) afin d'étudier les performances de deux prototypes de boucliers rigides utilisés dans les tranchées (BRUT) et fabriqués à contrat par deux compagnies canadiennes. Les deux prototypes ont été soumis aux détonations de dix obus à fragmentation d'artillerie de calibre 155 mm à sept mètres au-dessus des tranchées. Les détonations ont été effectuées de façon consécutive, et les systèmes de protection ont été réajustés après chaque détonation, lorsque nécessaire. Les résultats des tests sont présentés, brièvement analysés et discutés.

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EXECUTIVE SUMMARY

The Lightweight Enhanced Trench Overhead Protection System (LETOPS) task was initiated in 1992 to answer a Canadian Forces (CF) requirement for the development of a protective shield for soldiers entrenched in "foxholes" and subjected to enemy artillery fire. In such a situation, the standard trench configuration does not provide any overhead protection except that offered in the bottom of the trench by the roof of the shelter bay. Nevertheless, it is still required that the entrenched soldiers retain observation and firing capabilities when subjected to artillery fire. Trench overhead protection systems available on the market are very limited and offer little protection.

The LETOPS project was undertaken by DREV to design and develop a protection system that would meet the CF requirements. The project was divided into four phases: Phase I consisted in a Vulnerability Analysis (geometrical parameters); Phase II, performed in parallel with phase I, consisted in the determination of the ballistic protection requirements; Phase III was performed by two Canadian firms and consisted in the structural analysis, design and manufacture of two LETOPS prototypes; and Phase IV, which is the object of this report, consisted of the evaluation of the prototypes provided by the contractors. A fifth phase was later added to allow for the development of a special arrangement of LETOPS prototypes to provide protection above typical observation posts currently used by the CF in NATO peacekeeping missions.

An experiment was defined to characterise the protective capability of the prototypes when submitted to the consecutive detonation of ten 155-mm HE artillery shells situated seven meters above the trenches. Each prototype was installed above a distinct trench, and the shell was detonated at a median distance between the two trenches hence used. Various mannequins, lead heads and witness packs were used under the prototypes to obtain a variety of measurements.

It has been demonstrated that the survivability of entrenched soldiers would be dramatically improved by systems such as the LETOPS that offer sufficient ballistic protection. The project demonstrated the feasibility and the effectiveness of the prototype LETOPS devices.

1.0 INTRODUCTION

Canadian Forces doctrine is geared towards defence. When soldiers are under attack, the method used to protect them is to dig trenches so as to present a low silhouette and benefit from the protection the trench offers. To defend themselves, soldiers must also be able to fire their weapons from the trench. When soldiers are under attack, they are normally subjected to artillery fire which will require them to go in the sleeping bay and prevent them from using their weapons. To greatly improve the efficiency of the infantryman and to permit the most efficient use of the standard 0.6 m by 1.2 m trench in a defensive position, there is a requirement for a Lightweight Enhanced Trench Overhead Protection System (LETOPS) which would offer ballistic protection and some observation capability. A preliminary study of such a system was presented in Ref. 1.

In 1992, a project was initiated at Defence Research Establishment Valcartier (DREV) to investigate the feasibility of a LETOPS using advanced armour materials. The project was initially divided into four phases: Phase I consisted in a Vulnerability Analysis (geometrical parameters); Phase II, performed in parallel with phase I, consisted in the determination of the ballistic protection requirements; Phase III was performed by two Canadian firms and consisted in the structural analysis, design and manufacture of two LETOPS prototypes; and Phase IV, which is the object of this report, consisted of the evaluation of the prototypes provided by the contractors. A fifth phase was later added to allow for the development of a special arrangement of LETOPS prototypes to provide protection above typical observation posts used by the CF during NATO peacekeeping missions.

This report describes the trials performed within the framework of Phase IV of the project. The evaluation was performed at one of DREV's site, located at CFB Valcartier. This work was accomplished between September and November 1994 under the sponsorship of Task D MIL E 001.

2.0 LETOPS PROTOTYPES

At the end of an open call for bidding, two Canadian firms possessing a demonstrated expertise in advanced composite material design were selected for the analysis, design and manufacture of a LETOPS prototype. Wardrop Engineering Inc. is an engineering firm based Winnipeg (Man.). GID Design is an engineering firm based in Ste-Foy, in the neighbourhood of Québec City (Qué.). Both companies are committed to high quality engineering consulting services. The information provided on the companies was current as of November 1993. Phase III called for each company to produce one LETOPS prototype.

2.1 Requirements

The standard two-man battle trench used throughout the LETOPS project is illustrated at Fig. 1. It consists in a firing bay with an elbow rest, where the soldiers stand for observation and firing of their weapons. A "sleeping bay" or shelter bay is adjacent to the firing bay, and is used for rest periods as well as for covered protection during enemy's artillery fire. It is generally covered with approximately 60 cm of earth or sand. The following requirements were used by both contractors for the design of their respective prototype:

- Maximum weight of 200 kg in order to be transportable by two men in components not heavier than 80 kg each

- Resistance to the over pressure caused by a succession of fifteen (15) bursts of large calibre artillery shells detonating at 7 m. The system must maintain 90% of its original clearance after being submitted to the salvo of detonations

- Resistance to the penetration of fragments coming from large calibre artillery shells detonating at close distance: 95% over the central area of the shield; and 80% over the rest of the shield area

- Capability to support a static load imposed by the deposition of 0.6 m of sand bags on top of it

- Adjustable height between 0.3 and 0.6 m

- 360° observation capability and use of small arms while under cover

- Avoidance of metallic materials in order to minimise potential magnetic signature of the system

- Minimal dimensions as per Fig. 2. These dimensions are based on previous studies conducted at DREV (Refs. 2 and 3).
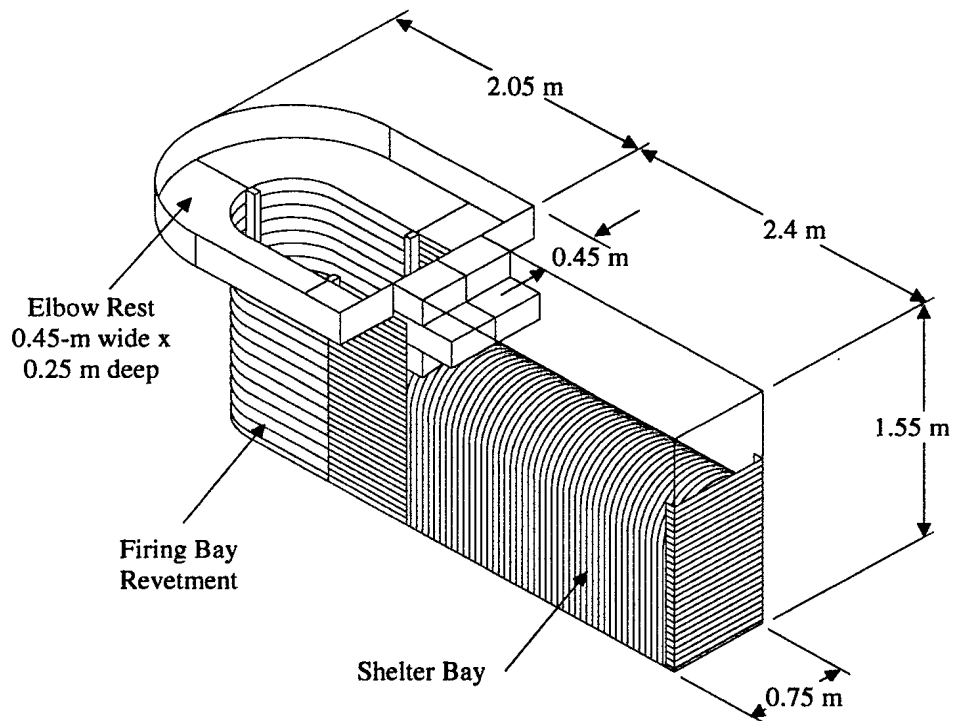

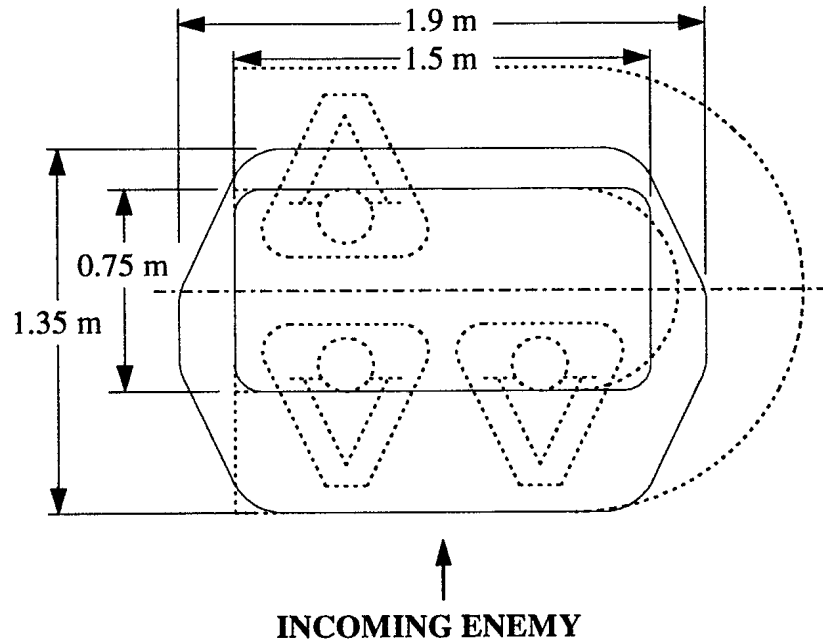FIGURE 1 - Standard two-man battle trench, type 3

FIGURE 2 - Minimum dimensions of the LETOPS
superimposed onto the trench contour

In order for both companies to design their ballistic panels to meet the required protection level (i.e. defeat at least 95% of all fragments from large calibre HE shells), an experimental program was carried out at DREV to translate the armour design requirement into the simpler requirement of defeating a fragment simulating projectile (FSP) of a given mass, called the **design FSP**. The approach followed to define the design FSP is described in Ref. 4. In summary, it is based on the measurement of the protection level of aluminium targets of various thicknesses and the knowledge of the maximum impact velocity of the fastest fragments generated by the static detonation of the specified HE shell (1172 m/s). The shell bursting velocity can then be computed and combined to the shell translating velocity, and corrected for air drag to arrive at a fragment design velocity of 1192 m/s. The design FSP mass was established at 42 g, which is 22% lower than the standard 20-mm FSP (54 g). Both companies were offered the possibility to experimentally validate their respective candidate materials using the design FSP as described above. Both companies accepted the offer and manufactured

armour samples for testing at DREV. The test results were then used to adjust the panel thicknesses on their respective systems.

2.2 Wardrop Engineering Ltd.

2.2.1 Company Background

Wardrop Engineering Ltd is based in Winnipeg (Man.) and employs 220 people in Winnipeg, Thunder Bay, and Toronto. They offer traditional engineering services as well as more specialised consulting services in various areas. For the purpose of this project, they teamed with a small polymer manufacturing company called Faroex Ltd, based in Gimli (Man.).

2.2.2 Prototype Description

The main characteristic of the Wardrop design was that it was all made of polymeric composites, without any metallic component. Wardrop investigated two different designs, and retained that consisting of a non-structural ballistic panel carried by a sandwich support panel. All the panels were flat for ease of design and manufacture. The structural sandwich support panel played the role a more conventional beam-structure would have otherwise played. It was 81-mm thick, and consisted of aramid top and bottom faces (each 3-mm thick) and a glass reinforced honeycomb core, for a total mass of 30 kg. The use of a structural panel was required since Wardrop/Faroex elected to go for a primary Kevlar panel optimised for its ballistic properties, which is generally detrimental to the structural properties (mainly due to the higher fibre content).

The ballistic panels were made from Kevlar 29 4x4 basket. Their dimensions were based on the minimum areas as defined at Fig. 2. The first panel had an areal density of 30 kg/m^2, for a total mass of 68.7 kg; while the second panel had an areal density of 56 kg/m^2 for a total mass of 62.5 kg. The total mass of the complete system (with legs, attachments, etc.) was 197.2 kg, while the maximum individual mass was 68.7 kg. The

three panels (one structural sandwich plus 2 ballistic panels) were all joined together by industrial Velcro® tape.

Leg inserts were bonded to the top and bottom faces of the structural plate to hold the leg in position. These legs were extensible through a threaded sleeve assembly to provide a clearance that could be varied between 300 and 600 mm. The height adjustment had to be done prior to final installation. All leg components were made from instant set polymer urethane (ISP) and manufactured by Faroex. As can be seen at Fig. 3, Wardrop and Faroex went for a foot with a hemispherical shape in order to ensure that the legs could be positioned easily in any kind of irregular soil surface. The feet also had apertures to allow for stakes and straps to be firmly attached to the legs. These straps were a key component for the stability of the prototype, as they secured it from the four corners.

The total fabrication cost of the system was estimated at approximately $31,500. This figure was based on the manufacture of a small number of units (5 to 10), and could be further reduced if a larger scale production was envisaged. A sketch of the Wardrop LETOPS is presented in Fig. 3. Complete details of the prototype can be found at Ref. 5.

2.3 GID Design

2.3.1 Company Background

GID Design is a group of 24 people offering consulting services in design and product development. Their mission is to design products that will meet their client's requirements. They have small shops for prototyping their solutions, but are not committed to serial production. Their services cover all phases of product development from strategic planning to industrialisation.
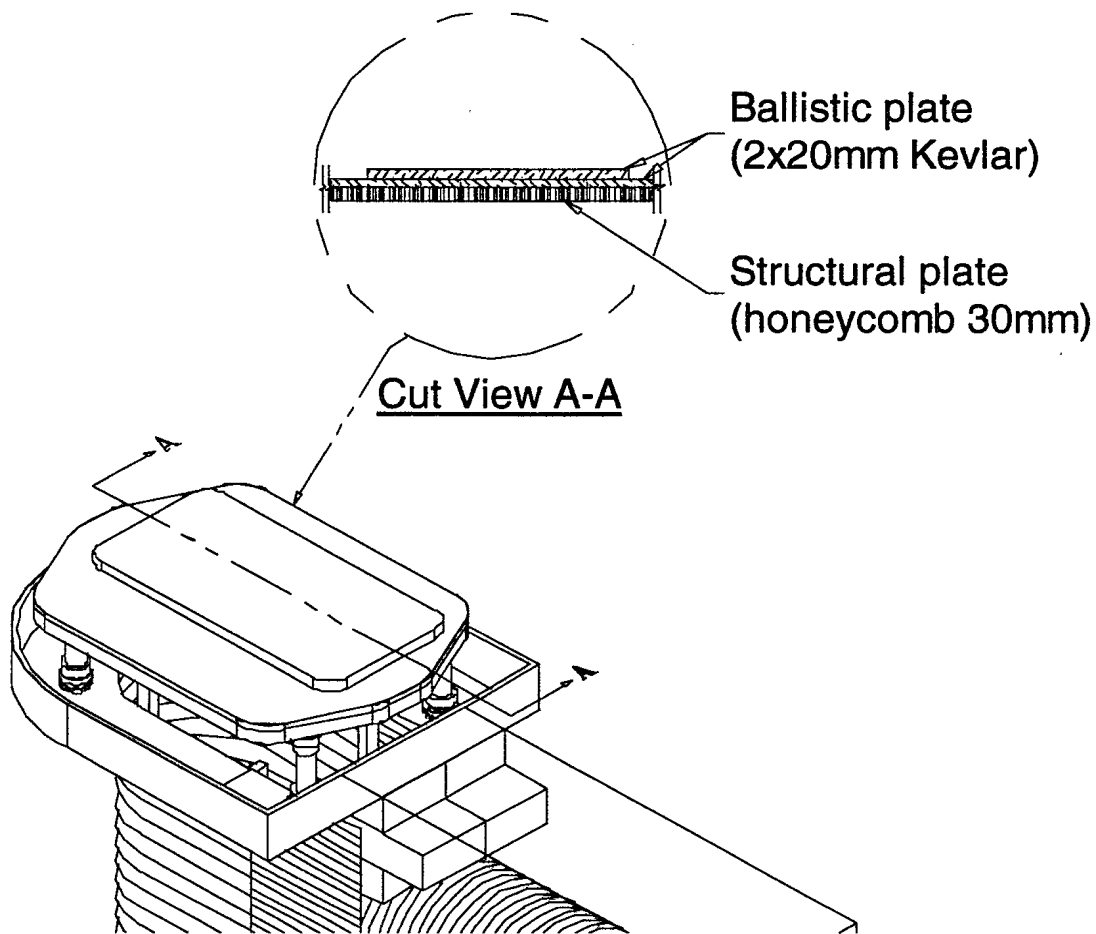
Ballistic plate
(2x20mm Kevlar)

Structural plate
(honeycomb 30mm)

Cut View A-A

FIGURE 3 - Sketch of the Wardrop LETOPS

2.3.2 Prototype Description

The GID system used more conventional solutions than those retained by Wardrop, in that it included metallic legs and metallic attachments supporting two ballistic panels. The structural plate was made of aramid (Kevlar 29, manufactured according to Ref. 6) with slightly larger dimensions than the minimum specified and shown in Fig. 2. The total mass of the structural plate was 81 kg. Since the Kevlar panel was used here both in the structural and the ballistic role, it was expected to be a little less effective at stopping fragments than the material used by Wardrop. A ballistic plate completed the assembly. This plate was made of 10 mm of 5083 aluminium armour. This is similar to that found on modern light armoured vehicles. The plate was bounded to the Kevlar panel

underneath and had a mass of 77 kg. Its dimensions corresponded to the minima specified and shown in Fig. 2. The total mass of the complete system added up to 206 kg, including all the attachments. The plates were joined together by the use of simple bolts and wing nuts. Both Kevlar plates were acquired from Sioux Manufacturing in North Dakota, U.S.A.. GID also investigated the possibility of using high density polyethylene (Dyneema) instead of Kevlar, but this solution was not retained for cost reasons. With the Dyneema material, it would be possible to further reduce the mass of the polymeric panels by approximately 20%, and reach the same protection level.

Aluminium legs were attached to the structural panel through sliding anchors. The four legs were made of tubular 6061 T6 aluminium. Each leg was in fact a jack very similar to what is found in the automotive industry. This permitted the elevation and lowering of the system to provide a clearance varying between 300 and 600 mm, even after the installation was complete. Flat cast aluminium feet are used to distribute the load on the ground. Steel cables were used on the prototype corners to secure the system to the ground, and increase its stability.

The total fabrication cost of the system is estimated at approximately $14,000. This figure is based on the manufacture of a small number of units (5 to 10), and could be further reduced if a larger scale production was envisaged. A sketch of the GID Design LETOPS is presented at Fig. 4. Complete details of the prototype can be found in Ref. 7.
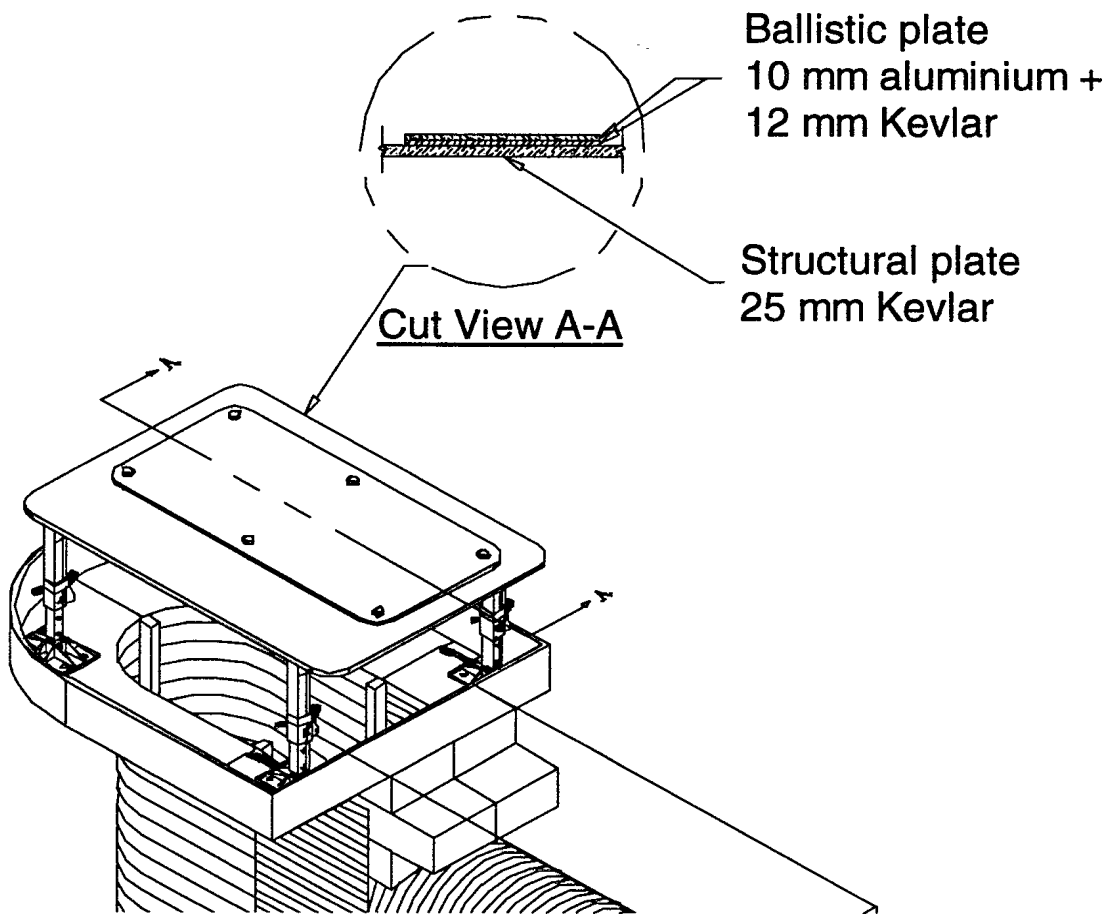
**Ballistic plate
10 mm aluminium +
12 mm Kevlar**

**Structural plate
25 mm Kevlar**

Cut View A-A

FIGURE 4 - Sketch of the GID Design LETOPS

3.0 TEST DESCRIPTION

3.1 Test Set-Up

All the tests reported here were conducted on the tank park area of the DREV range adjacent to CFB Valcartier. In order to evaluate the effectiveness of both systems at the once, an arrangement of two trenches facing each other was prepared. Both the parapet (elbow rest) and the steel revetments were used for the construction of the trenches. Each prototype was located above a trench. The artillery shell was located at the centre of the two trenches, at a height of 7.52 m above the ground. This corresponds to a 7.2 m slant distance to the middle of the top for each prototype system. As shown in Figs. 5 and 6, a

wooden A-shaped frame system was used to hold the artillery shells in position. The frame was replaced after each test, and was made of two 8.2-m long wood beams built using 50 - 150 mm (2 x 4 in) pieces nailed together in an H geometry for better stiffness. The legs of the frame were attached with a steel fixture to two concrete blocks six meters apart. The steel fixture was designed to allow the frame to be assembled on the ground, and then easily put up. Once raised, it was secured to the ground with four nylon cables. The projectile was mounted on a fixture that allowed its vertical elevation to be adjusted to the desired angle. The support fixture and the wooden frame were designed to provide the least possible interference with the fragmentation of the bursting shell.

Also shown on Fig. 5 are the two mannequins that were placed underneath the GID Design prototype in order to get preliminary data on the result of perforating impacts on the personnel protective equipment when used in conjunction with such an overhead protection system. Mannequins were not used under the Wardrop prototype to limit the instrumentation used. The mannequins were made up from wooden boxes with lead heads seated on top of them. On some occasions, the mannequins were also placed inside the protection (or sleeping) bay, to observe the differences in the data obtained. The primary objective of using wooden mannequins and lead heads was to hold pressure gages, one at the thorax level and another at ear level. The secondary objective was to evaluate the number, hit area and approximate size of the fragments that would eventually perforate the LETOPS and reach the personnel inside the trench. The mannequins were placed inside the trench and impact information was recorded for rounds number 1 through 9. The mannequin # 1 and # 2 were installed back to back as showed on Fig. 5. A high speed camera was also used during the trials to ensure that the transient deformations of the LETOPS panels were not excessive.

SIDE VIEW

WOOD FRAME

FRAGMENT
VELOCITY
MEASUREMENT
SYSTEM

15°

7.2m

1.83 m

1.83 m

CONCRETE
BLOCK

CONCRETE
BLOCK

TRENCH

PROTOTYPES

TRENCH

SIDE VIEW

10°

155-MM HE
FRAGMENTING SHELL
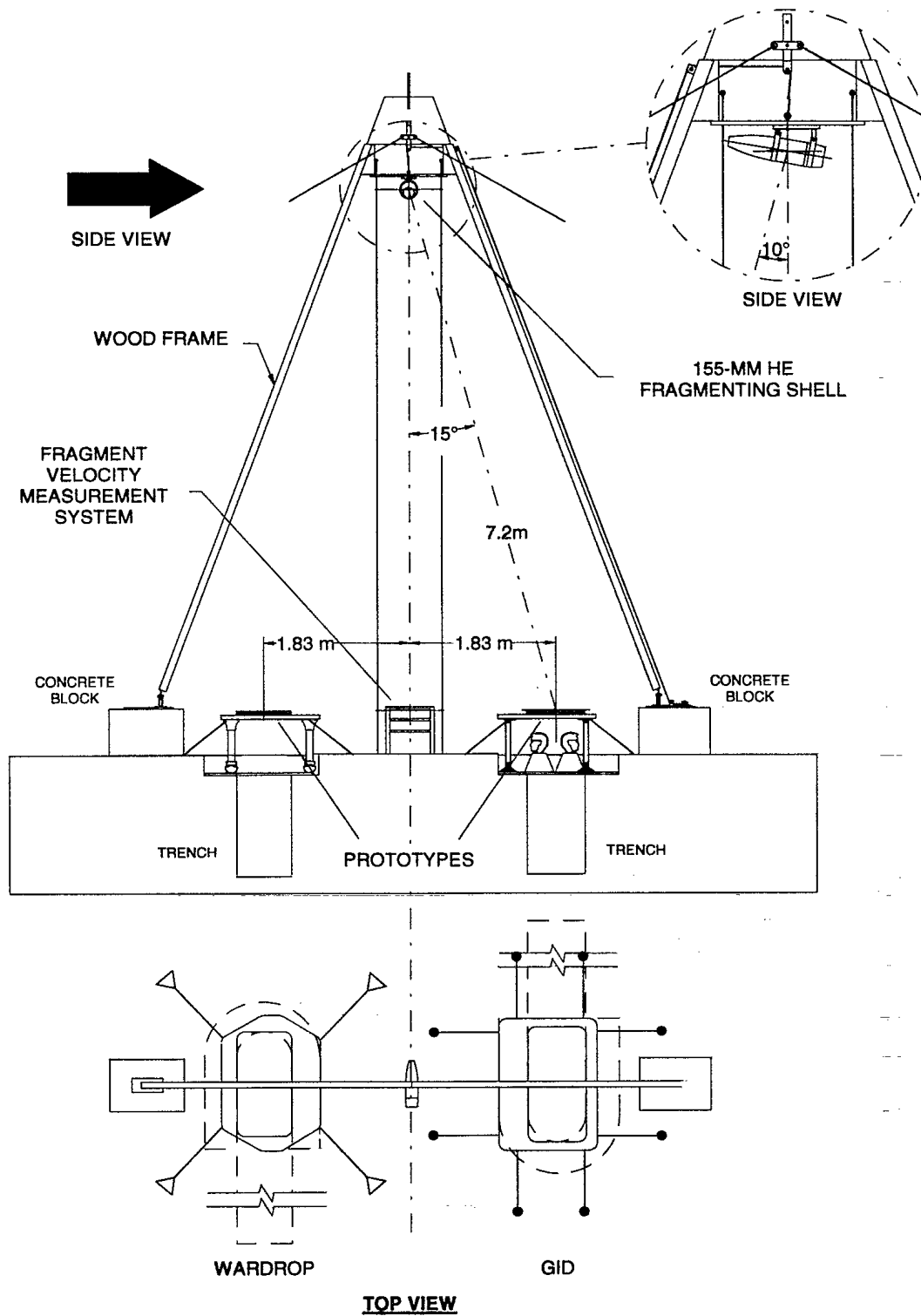
WARDROP

GID

TOP VIEW

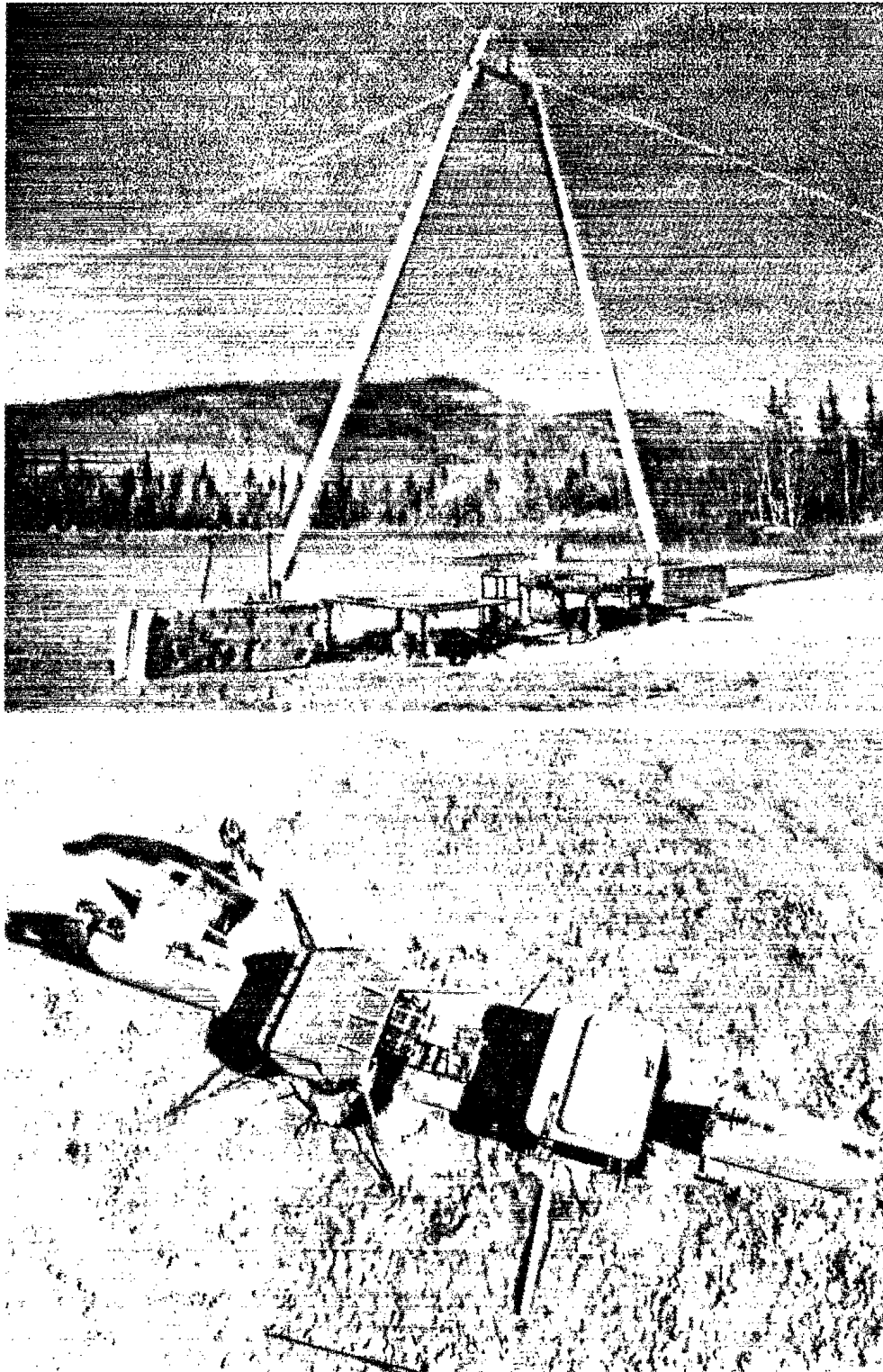FIGURE 5 - Setup used for the trials

FIGURE 6 - Pictures of the setup

3.2 155-mm HE Artillery Shell

For the testing, it was decided to use 155-mm M107 High Explosive (HE) artillery shells (6.95 kg COMP B). This shell is generally deemed representative of the Russian 152-mm HE artillery shell, or a little more severe. The ten rounds used included the standard supplementary charge (0.15 kg COMP A3). The projectile fuses were replaced by a booster charge consisting of one pellet (5.4 g) of Tetryl and one pellet (20 g) of RDX fitted in a plastic container. The projectiles were statically detonated using electric blast caps and a high voltage source. The detonation was triggered remotely from a firing bunker. To ensure that the largest number of fragments generated by the warhead would hit the two LETOPS prototypes for each event, the projectiles' nose was oriented 10° upward. Fragmentation data available on this warhead indicated that the maximum number of fragments are generated from this angular orientation of the warhead.

4.0 TEST RESULTS

A total of ten (10) rounds were detonated consecutively above the two trenches. This scenario was determined by the sponsor as a worst-case scenario. Although it was initially planned to detonate a total of 15 rounds, it rapidly became obvious that the test was too severe and unrealistic. This will be discussed in section 5 of the report. The decision to stop the series was then taken after the tenth round.

4.1 Assembly

Both systems were heavily affected by the series of detonations above the trench. In fact, the trench itself was quite disturbed after each detonation: earth and trench revetment movements were common. These movements had a direct impact on the stability of the prototypes, and could have proven detrimental. One could argue that it would have been more realistic to leave the systems unadjusted for the complete salvo to which they were to be submitted. It however became obvious early in the test series that the conditions used (salvo of 10 to 15 rounds detonating 7 m high, directly above the trench) was not a

realistic scenario. Since the purpose of the tests was to evaluate the behaviour of the prototypes when properly installed, it was decided to readjust them whenever required in between the rounds. This means that the straps and cables were also retightened after each round. Observations were however taken after each detonation to ensure that obvious deficiencies in the design would be duly noted and could be corrected in the advanced development phase.

4.1.1 Wardrop prototype

As stated at par. 2.2.2, Wardrop selected Velcro® tape to attach the various panels together, and even used Velcro® straps to secure the system. It soon became obvious that this type of attachment is not very well suited for this application. As soon as the tape comes in contact with mud and earth, it loses much of its efficiency since the hook an loops become clogged. Cleaning both sides of the tapes was quite difficult in field conditions.

The legs also posed minor problems when it was time to screw them into the structural panel inserts. A strap-wrench had to be used, since it was not easy in some cases, and impossible in others, to do it by hand. The instructions provided to the users stated that the legs could be inserted by hand. It was also noted that the threaded part of one of the legs had to be cleaned using solvent since it appeared that some resin (or glue) had been left uncleaned upon manufacturing.

4.1.2 GID Design prototype

The GID prototype was easily assembled by following the instructions provided. No specific problem was encountered during the assembly process, which was quite straightforward using the simple mechanical fasteners used by GID. It was however noted that there is a large number of small and loose parts that could be easily lost in the field during unpacking and assembly.

4.2 General Behaviour

4.2.1 Wardrop prototype

The stability of the Wardrop prototype was quite severely affected after the very first detonation. It appears that one of the leg feet penetrated the sandbags put underneath to build up the trench contour. This seems to be due to the shape of the feet. While the feet permit adaptation to various field conditions, they did not necessarily provide the required stability when submitted to the warhead blast overpressure. Due to the movement caused by the leg displacement, two threaded sleeves used to attach the legs to the structural plates were detached. The legs were fixed (basically put back in position without gluing them) and the prototype was repositioned prior to the next round. Apart from the above observations, the system remained intact and resisted quite well the fragment impacts.

No special observations were made for the next two rounds, apart from the fact that the complete system was slightly sunk into the ground (in the order of 3 to 5 cm). Already after the fourth detonation, it was a difficult task to identify the new impacts on the Kevlar panels, due to the fibre fracture and the extensive surface damage on the laminates external envelope. On the fifth round, a small part of the structural panel was ripped off the prototype by one or more fragments hitting it on the edge.

The prototype remained unaffected and fairly stable for the following three rounds. On the ninth round, one of the legs failed at the joint level. The system was simply secured in position without further repair, mainly by readjusting the tension in the straps. The system was then submitted to the tenth round without significant change.

4.2.2 GID Design prototype

One of the steel cables used to secure the prototype in position was sectioned by a fragment right on the first round. The cable was easily replaced, and the system was secured in position for the next round. No special observation was made after the second round. After the third round, it was noted that the Kevlar plate (acting both as a structural

and ballistic plate) started to bend due to the blast overpressure. It was also noted that the latch on one of the legs was broken and not functional anymore.

After the fourth round, it was noticed that the four cast-aluminium feet were either cracked or broken, and started to provide less than adequate support to the legs. It was also noted that the permanent bending of the structural Kevlar plate was becoming more important. The bending of the Kevlar plate continued to increase, and noticeable delamination became obvious on the edges of the plate. It was also suspected that the plate was fractured in the centre. The legs are also becoming unstable due to the fracture of the feet. This also had an influence on the attachments on the Kevlar plate that were submitted to undue stress due to the leg movements. The stability of the prototype is accomplished only through the steel cables securing it all around.

After the sixth round, the leg attachments were now severely affected and were starting to break. At the seventh round, the legs were practically detached from the Kevlar plate, the attachment having been ripped off by the stress due to the leg movements. The Kevlar panel was now severely bent and broken in the centre. Much of the structural role was now played by the aluminium/Kevlar plate bolted onto the Kevlar plate.

At the eighth round, the bending at the centre was now in the order of 10 cm. The situation remained unchanged for the next two rounds. The prototype was held in position only by the mechanical attachments to the aluminium plate and the steel cables around it.

4.3 Perforation Results

Although it was quite easy to count the total number of perforations on each prototype, the situation is different for the determination of the total number of impacts that did not achieve a complete penetration of the panels. The perforations (by definition a **perforation is a complete penetration**) can be determined from the number of holes observed underneath the bottom panels. The bottom surface remains relatively undamaged due to the small number of perforations. The top surfaces are however much

more extensively damaged due to the large number of impacts experienced after the ten rounds. Due to the nature of the materials used by GID Design for the secondary ballistic panel (aluminium/Kevlar), it was relatively easy to determine the total number of fragment impacts on it, even when the trials were completed. Although it is acknowledged that some fragments might have hit directly into holes already produced by previous fragment impacts, it is deemed that the accuracy obtained is sufficient for the purpose of this evaluation. Hence a density of impacts ρ_I was computed from the observations on the aluminium panel, and this density was used to compute the total number of impacts on the composite panels as well. It was deemed that doing so was more accurate and realistic.

For each prototype, two protection levels were computed: one without the secondary ballistic panel, and the other with all the ballistic panels combined together. This then gives an indication of the level of protection of the largest area of the LETOPS, without the ballistic reinforcement provided only for a limited area of the system. The protection level represents the percentage of fragments that are effectively stopped by the system. It is computed according to equation I:

$$PL = 100x\left(1 - \frac{p}{i}\right) \qquad [\text{I}]$$

where: PL is the protection level

p is the total number of complete perforations

i is the total number of impacts

For the protection level of the first ballistic panel, only the impacts located outside the secondary ballistic panel area were taken into account. The protection level provided by the combination of the two ballistic panels was computed considering the number of perforations in the first ballistic panel, but located inside the secondary ballistic panel profile on the first panel (i.e. underneath the secondary ballistic panel), and the total

number of impacts on the secondary ballistic panel, computed from the density of impacts ρ_I.

4.3.1 Density of impacts ρ_I

The density of impacts ρ_I was computed by dividing the total number of impacts (after ten detonations) on the aluminium plate of the GID Design prototype by the area of the plate. It was found to be 191.9 impacts/m². Hence 192 impacts/m² was used for the computation of the protection level of all plates, taking into account their respective presented areas.

4.3.2 Wardrop prototype

Figure 7 shows the location and approximate size of the holes observed in the primary ballistic panel of the Wardrop prototype. Due to the nature of the materials used in this system, it was not possible to record all the impacts on the panels; hence only the complete perforation are reported. Superimposed in dotted lines is the profile of the second ballistic plate as it was positioned during the trials. Based on these observations, it was determined that the protection level of the primary panel is 77%, while that of the two panels combined is 85%.

4.3.3 GID Design prototype

Figure 8a shows the location and approximate size of the impacts noted on first the ballistic panel (made of Kevlar and aluminium) of the GID Design prototype. Superimposed in dotted lines is the profile of the second ballistic plate (aluminium) as it was positioned during the trials. Figure 8b shows the location and approximate size of the impacts noted on the secondary ballistic panel. The partial penetration are marked in blue, while the complete perforations are marked in red. Based on these observations, it was determined that the protection level of the primary panel is 72%, while that of the two panels combined is 97%.
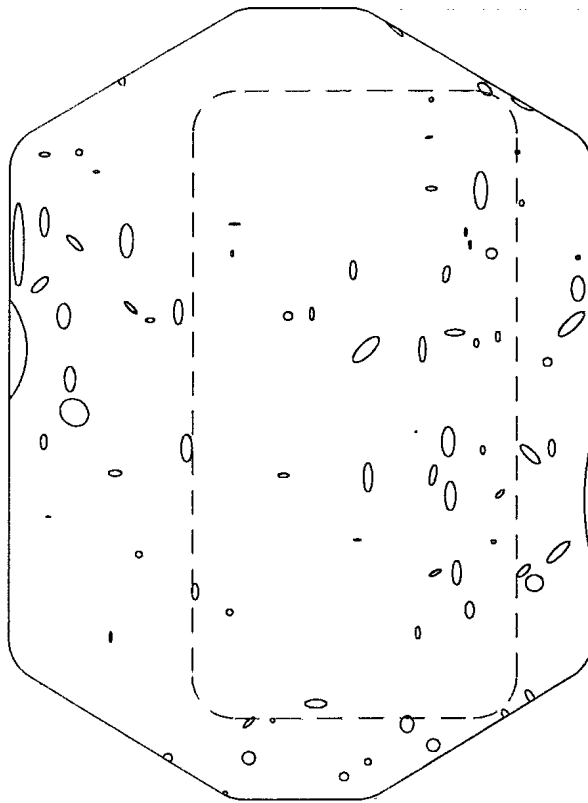
FIGURE 7 - Perforation pattern on the Wardrop prototype

4.4Observations on the Mannequins

4.4.1 Fragment Impact

Throughout the trials, it was noted that a great amount of soil was projected towards the mannequin in the firing bay. In some case, sand bags did stop some fragments, but because of the geometry of the firings, it was doubtful that those fragments would hit the personnel.

The hits observed were concentrated on the head (top and side), neck, top of the shoulder and upper back. Some hits were also recorded at the thorax and waist level. The size of the holes left by the fragments varied from 4 to 5 cm for the bigger fragments. Some smaller fragment (less then 1 cm) hits were also recorded, but in limited number. Most of

the fragment hits observed were between 1 and 3 cm in size. Over the 8 shots for which mannequins were placed in the firing bay, fragment hits were observed on shots 2, 3, 7, 8 and 9. Overall, 41 hits on the mannequins were observed during the events, as detailed in Table I.

a) Impacts on the primary
     ballistic panel
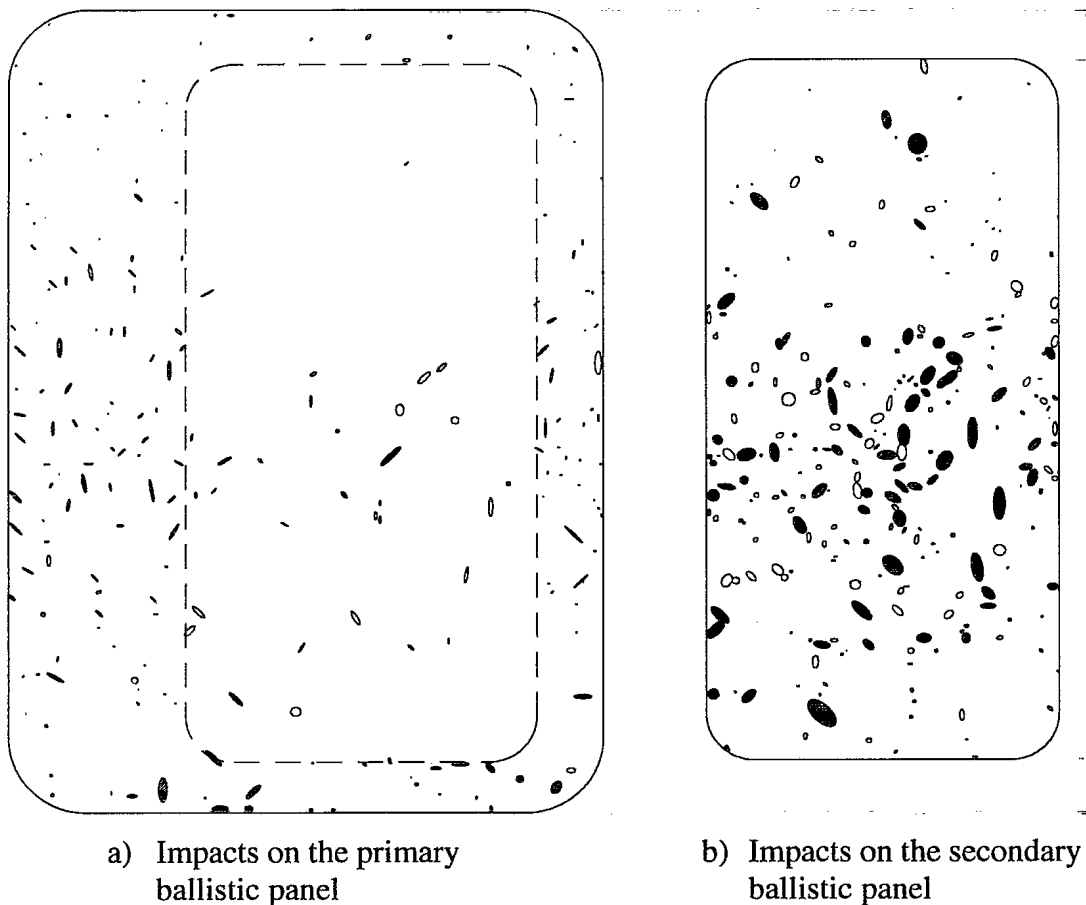
b) Impacts on the secondary
     ballistic panel

FIGURE 8 - Impact patterns on the GID Design prototype panels

The larger number of impacts on mannequin # 1 with respect to mannequin # 2 can be explained in the following ways. First, mannequin # 1 was mainly protected by the less resistant primary ballistic panel while mannequin # 2 was completely covered by both panels (see Figure 5). Second, it was very difficult to estimate the direction from which the incoming fragments were arriving. It is suspected that some fragments might have

ricocheted on the ground before hitting mannequin # 1. The presence of sand bags on the side of the trench and a better adjustment of the height of the LETOPS could have reduced the number of indirect hits (ricochets) on mannequin # 1.

TABLE I

Main characteristics of the two prototypes

Trial #	Mannequin #1	Mannequin #2	Total	Comments
2	10	0	10	Observed on bare wood
3	2	4	6	Observed on bare wood
7	13	2	15	Observed on Kevlar ballistic vest. No head
8	4	0	4	Observed on Kevlar ballistic vest. No head
9	3	3	6	Observed on Kevlar ballistic vest. No head
Total	32	9	41	

4.4.2 Blast Pressure Effects

Blast overpressure data were recorded during all of the 10 shots. For firing 1 to 5, pressure gauges were placed on the mannequins in the firing bay. For firings 6 to 10, the pressure gauges were placed on the mannequins in the protection bay. The mannequins were placed inside the trench as illustrated in Figure 9. The objective was to determine if the presence of the LETOPS would enhance reflections of the blast wave such that it could incapacitate the personnel inside the trench. Only primary injuries to the lungs and ear were investigated.

When placed in the firing bay, mannequin #1 had the ear pressure gauge placed in the left ear while mannequin #2 had it placed in the right ear. When placed in the protection bay, the positions of these gauges was reversed, that is for mannequin #1 it was placed in the right ear, and in the left ear for mannequin #2. Table II summarize the pressure wave data

recorded on the heads and thorax. The data from firings 2 to 7 and 10 were filtered through a low pass numerical filter at 300 Hz to cut off high frequencies and to smooth the curves. Data from firing 8 and 9 did not require any filtering as they were usable as is.
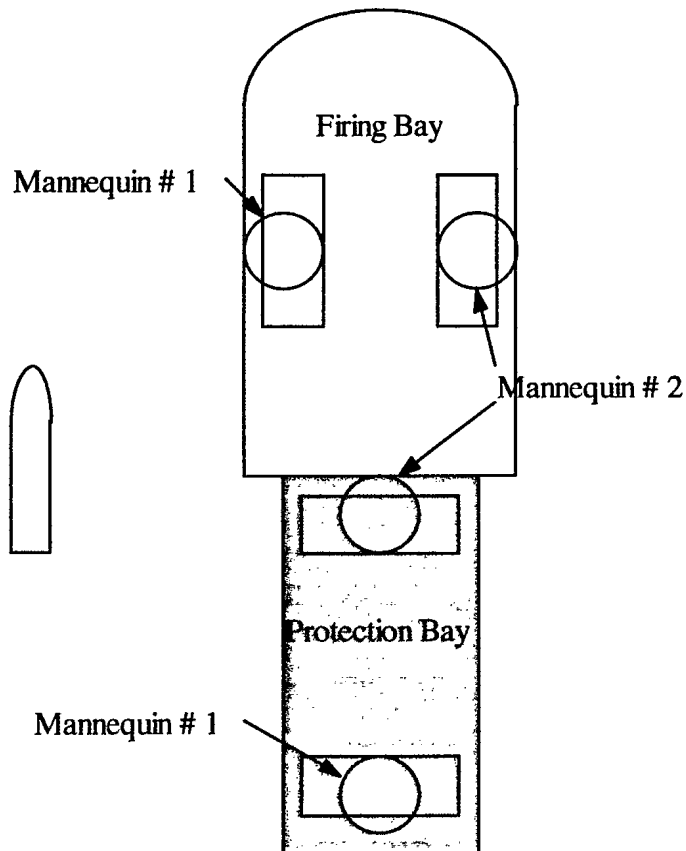

FIGURE 9 - Position of the mannequins

One can observe from these results that the pressure level and the duration of the blast waves are not sufficient to cause incapacitation from lung damage, either in the firing bay or the protection bay. In Ref. 8, the threshold for lung damage is specified as 15 psi for long duration (more than 40 ms) blast waves. For shorter duration blast waves, the threshold is even higher, i.e. 20 psi for 10-ms waves. The pressure level and duration read from the gauges on both mannequins in the firing bay are very similar, mannequin # 2 showing slightly higher pressure levels (by only 1 to 2 psi). For the mannequins in the protection bay, the pressure levels are about the same as for the mannequins in the firing

bay, but with much longer duration, especially for mannequin # 1 close to the end wall of the protection bay. The difference in pressure levels comes from the wave reflection on the end wall of the bay and the difference in the duration comes from the air filling effect in the protection bay cavity.

TABLE II

Overpressure data

Trial #	Position in trench	Organ considered	Positive pressure	Duration	Incapacitation probability
			(psi)	(ms)	(%)
02	FB[1]	Lungs on man. #1	2.4	4.4	0.0
02	FB	Ear on man. #2	6.5	2.6	40
02	FB	Lungs on man. #2	11.7	17.3	0.0
03	FB	Lungs on man. #1	3.7	5.4	0.0
03	FB	Lungs on man. #2	4.7	4.6	0.0
04	FB	Ear on man. #1	1.7	4.3	10
04	FB	Ear on man. #2	3.9	5.1	24
04	FB	Lungs on man. #2	5.2	6.2	0.0
05	FB	Lungs on man. #1	3.0	5.8	0.0
05	FB	Ear on man. #2	5.4	5.2	34
05	FB	Lungs on man. #2	5.5	5.2	0.0
06	PB[1]	Lungs on man. #1	3.2	22.5	0.0
06	PB	Lungs on man. #2	2.4	9.7	0.0
07	PB	Lungs on man. #1	3.0	17.8	0.0
08	PB	Ear on man. #1	3.0	19	19
08	PB	Lungs on man. #1	3.4	17	0.0
09	PB	Ear on man. #1	3.3	22	21
09	PB	Lungs on man. #1	4.55	21	0.0
09	PB	Lungs on man. #2	10	16	0.0
10	PB	Ear on man. #1	2.9	22	18
10	PB	Lungs on man. #1	3.3	13	0.0
10	PB	Ear on man. #2	1.5	15.4	8
10	PB	Lungs on man. #2	2.6	8.6	0.0

FB= Firing Bay; PB = Protection Bay

The blast waves recorded at the ear level show substantial incapacitation probabilities (10 to 40%) for the mannequins in the firing bay, especially for mannequin # 2. The incapacitation probability presented in Table II are for unprotected personnel (no ear protection). Pressure data on the mannequins in the protection bay also show significant incapacitation probabilities caused by the loss of hearing (8 to 21%). Once again, mannequin # 1 in the protection bay sustained higher pressure and longer duration wave then mannequin # 2. Adequate ear protection would considerably reduce the incapacitation probabilities(1% and lower).

It is interesting to note that the pressure data demonstrate higher pressure readings for mannequin # 2 with respect to mannequin # 1 at the thorax and head level in the firing bay. Simulations performed with a Computational Fluid Dynamic code (IFSAS) agreed with these results. It should be remembered that as the LETOPS is not placed symmetrically above the trench longitudinal axis, mannequin #1 gets more coverage (see Figure 5). Mannequin #1 is thus more affected by the filling pressure of the trench than by the reflections on the ground. This effect is reversed for mannequin #2. One could expect that the presence of the LETOPS can considerably reduce the level of the peak pressure experienced in the trench by reflecting back a part of the blast wave away from the trench. Simulations demonstrated a 50% reduction of the peak blast overpressure in the trench when the LETOPS is used. Based on Ref. 9, the calculated expected incident pressure on the mannequins is 7.8 psi and the peak normally reflected wave is 19 psi. Both are higher then the measured pressure under the LETOPS in the firing bay. Thus, the presence of the LETOPS does procure a certain level of blast protection.

5.0 DISCUSSION AND ANALYSIS

The main characteristics of each prototype are presented at Table II. This data was obtained/computed from measurements taken on the prototype rather than using the data provided by the manufacturers in their final report (Refs. 4 and 5).

5.1 Structural integrity

As was outlined in section 4.2, the integrity of each system was severely affected by the consecutive detonations above the trenches. It however needs to be outlined here that the tests to which both prototypes were submitted are extremely severe, and are certainly much worst than what should be expected on the battlefield. In reality, it is difficult to foresee a scenario where a series of detonations like this would detonate as close as that, in more than one or two occasions. It is indeed much more realistic to expect one or two detonations occurring directly above the trench, 7 m above the ground if a proximity fuse is used, and the rest of the salvo detonating at various distances from the trenches, still 7 m above the ground. On the other hand, there is also the possibility that a contact fuse would be used, which in the case of a direct hit would be disastrous in any case for a 155-mm shell, and against which it is not possible to design adequate protection. The structural behaviour of the prototypes is directly linked to the combined effect of blast overpressure and fragment impacts to which they are submitted. As blast overpressure is inversely proportional to the third power of the distance, one can easily figure that it rapidly becomes less severe as the distance from the trench increases.

This does not alleviate the need for the designers of both systems to review the results of the trial and improve the points that were identified as obvious weaknesses. The major flaw observed in both cases is related to the legs. In both cases, the link between the legs and the structural panel failed after a few detonations (inserts for Wardrop, and slides for GID). Although one can recognise the ease of use of both systems (particularly that of GID), it is more important to ensure that these links will resist the blast of the detonations. These two criteria (ease of use and robustness) are however not deemed incompatible and it should be possible to improve the design to reach the desired level of performance. The other point is related to the feet used by both designers: the hemispherical foot used by Wardrop made it quite stable initially, but quickly prove inadequate to sustain adequate stability when submitted to the blast; the flat foot made of

cast aluminium used by GID were too weak at the leg joint, and quickly failed after a few detonations.

TABLE III

Main characteristics of the two prototypes

Prototype		Wardrop	GID Design
Main materials		Kevlar	Kevlar & Aluminium
Total mass	(kg)	197.2	206
Primary ballistic panel	Mass (kg)	68.7	81
	Area (m²)	2.214	2.521
	Areal Density (kg/m²)	31	32
Secondary ballistic panel	Mass (kg)	62.5	77
	Area (m²)	1.116	1.297
	Areal Density (kg/m²)	62	62
Protection level	Primary panel alone (structural)	77%	72%
	Primary + Secondary panels	85%	97%

The structural integrity of both prototypes was also largely related to the straps/cables used to secure them on the ground. If these devices were sufficiently damaged (i.e. more than one strap/cable that would fail), there us a high probability that the structural integrity would be compromised. The LETOPS would be less vulnerable it its dependency on the supporting straps/cables was eliminated, or at least reduced. Although estimates of the total blast and fragment impact loading were provided to the contractors, it appears that the dynamic combination of both phenomena is to complex to be simply modelled using conventional quasi-static finite element methods, as demonstrated by the

failure observed on various components. Again, it is necessary to repeat that the testing scenario used was unrealistic, and should be revised in further programs.

Another observation that can be made is related to the attachment system between the primary and secondary ballistic panels. It rapidly became obvious that a system such as Velcro® is not suitable for this type of use. Mechanical attachments such as the wing nuts and bolts used on the GID Design prototype has the advantage of being simple and robust. It also offers the possibility to take some charge whenever the primary panel (or structure) starts to fail. It however has the disadvantage to present several small parts that can be easily lost during assembly and disassembly (problem that can however be overcome relatively easily). It was also observed that the number of bolts securing the ballistic plate to the structural one should be increased to improve the stiffness of the system, by preventing excessive bending of the structural plate.

5.2 Ballistic protection

As can be observed from the penetration results, none of the two prototypes completely fulfilled all the initial requirements (80% for the primary panel, and 95% for the secondary panel). However, the protection level achieved by the GID Design prototype with both panels in the central area is more than adequate, and demonstrates the feasibility to obtain the desired protection level. Indeed these results outline the advantage of using a hybrid metallic/composite panel against artillery shell fragments since at an equivalent areal density, the aluminium/Kevlar combination outperforms Kevlar alone as secondary ballistic panel (see Table I). The better performance observed might also be partly due to the difference in primary ballistic panel material used, as that used by GID has better structural properties than that used by Wardrop. Fine tuning of the primary panel could probably lead to the 80% requirement for the primary panel alone. It seems to be more difficult to reach the highest protection level using composite materials alone. The use of aluminium in the panel might be a necessity for this type of application. The protection level achieved by such a system could also be improved by

the use of better aluminium alloys (such as the 70XX and the 25XX series) or even titanium alloys.

Due to the nature of the mannequins used (wood boxes and lead heads), it is very difficult to try to extrapolate the level of incapacitation that would have been experienced by the soldiers submitted to the impacts observed. It is sufficient here to state that the soldiers would have been sufficiently incapacitated to prevent them to continue their observation and firing activities. As has also been said in previous sections, the testing scenario was used mainly to determine the ballistic protection level afforded by the systems, and was not realistic enough to draw any conclusion on the fragment impacts observed on the mannequins.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The final tests on the prototypes prepared by two different contractors demonstrated that it is feasible to design a trench overhead protection system in such a way that it may be transportable by two men, resist the attack of an artillery salvo, and provide the ballistic protection that will highly enhance the survivability of the infantrymen entrenched in a foxhole. Although the concepts have been demonstrated, much refinement work remains to be done in order to arrive at a final product that can be manufactured on a large scale. It however seems to be possible to arrive at an acceptable system at a cost in the 10K$ to 15K$ range. It would also be possible to obtain a design that is more easily transportable by using a 3-panel system. The performance of the proposed system against direct hits by mortar warheads and small calibre projectiles will also need to be investigated

7.0 ACKNOWLEDGEMENTS

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ABSTRACT
This report describes a test program completed at Defence Research Establishment Valcartier (DREV) to study the performance of two Lightweight Enhanced Trench Overhead Protection Systems (LETOPS) prototypes manufactured under contract by two Canadian firms. Both prototypes were submitted to the detonation of ten 155-mm HE artillery shell seven meters above the trenches. The detonations were performed consecutively, and the systems were adjusted after each detonation, whenever required. The test results are presented, summarily analysed and discussed.

RÉSUMÉ
Ce rapport décrit un programme expérimental récemment complété au Centre de recherches pour la défense Valcartier (CRDV) afin d'étudier les performances de deux prototypes de bouclier rigide utilisé dans les tranchées (BRUT) fabriqués sous contrat par deux compagnies canadiennes. Les deux prototypes ont été soumis à la détonation de dix obus à fragmentation d'artillerie de calibre 155 mm sept mètres au-dessus des tranchées. Les détonations ont été effectuées de façon consécutive, et les systèmes de protection ont été ajustés après chaque détonation, lorsque requis. Les résultats des tests sont présentés, brièvement analysés et discutés.

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